

An effective look at right-handed currents and quark flavour mixing

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We present an effective theory approach for a model with a left-right symmetric flavour group broken only by the Yukawa couplings. An underlying $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ global symmetry is assumed without specifying the fundamental theory. The model is motivated by the fact that the $|V_{ub}|$ problem can be solved by assuming the existence of right-handed (RH) currents. In this framework the flavour mixing in the RH sector is given by a new mixing matrix. After a short introduction of the model, we show how this RH mixing matrix can be determined by theory, experimental data and phenomenological constraints. We summarize the results of the RH contribution to flavour mixing in $\Delta F = 2$ processes. Furthermore we briefly discuss $Z \rightarrow b\bar{b}$ and the rare decays $B_{s,d} \rightarrow \mu^+\mu^-$, $B \rightarrow \{X_s, K, K^*\}\nu\bar{\nu}$ and $K \rightarrow \pi\nu\bar{\nu}$ with corresponding correlations.

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1 Introduction

Right-handed currents are known to arise in various new physics scenarios, particularly in models with an underlying $SU(2)_R \times SU(2)_L$ symmetry. However here we follow a different approach. Recently, right-handed currents have also been shown to resolve the tension between inclusive and exclusive determinations of the $|V_{ub}|$ element of the CKM matrix (for example see [1]). Motivated by this work we consider RH currents in an effective theory approach, assuming a left-right symmetric flavour group which is broken only by the Yukawa couplings. A new unitary matrix controlling flavour-mixing in the RH sector appears, whose structure can be determined by charged-current data. We analyse the impact on neutral-current flavour-violating processes in particle-antiparticle mixing, $Z \rightarrow b\bar{b}$ and various rare decays. A more detailed analysis can be found in [2].

2 The RHMfV model

In the Right-handed Minimal Flavour Violation (RHMfV) model introduced by [2] an effective theory approach is considered in the spirit of [3]. However, we choose a left-right (LR) symmetric flavour symmetry $SU(3)_L \times SU(3)_R$ which is broken just by the Yukawas, similar to the MFV case. In this approach the fundamental theory is not specified, and we only make assumptions about the global symmetry and the pattern of breakdown. In order to make the minimal model, the Standard Model (SM) gauge group is embedded into a global $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ group, where only $SU(2)_L$ and $U(1)_Y$ are effectively gauged below the TeV scale. Figure 1 compares our model with respect to MFV. RHMfV is clearly beyond MFV if considered in comparison to the $SU(3)^3$ quark flavour symmetry of MFV. However if we go to the LR symmetric flavour group, then it is MFV in a sense as the symmetry is again just broken by the Yukawas.

In the next step all dimension six operators formally invariant under the LR symmetric flavour group are considered. New bilinears arise with respect to MFV e.g. $\bar{Q}_R \Gamma Y_u^\dagger Y_u Q_R$. In this bilinear the Yukawa insertion $Y_u^\dagger Y_u$ is present, characterizing the strength of RH mediated flavour changing neutral currents (FCNCs) and containing elements of a new RH mixing matrix \tilde{V} . This matrix \tilde{V} appears due to misalignment of the Yukawas in the down-type sector and controls the RH flavour mixing. It can be parametrized as follows

$$\tilde{V} = D_U \tilde{V}_0 D_D^\dagger, \quad (1)$$

where \tilde{V}_0 is a CKM like matrix and $D_{U,D}$ are two diagonal matrices, with five more new CP violating phases in particular $D_U = \text{diag}(1, e^{i\phi_2^u}, e^{i\phi_3^u})$ and $D_D = \text{diag}(e^{i\phi_1^d}, e^{i\phi_2^d}, e^{i\phi_3^d})$. Altogether there are three new real mixing angles and six new

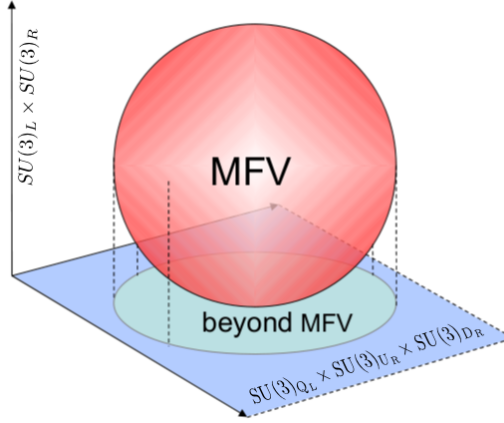


Figure 1

complex phases. This matrix is restricted by various bounds, which I want to discuss in the following in detail .

Using the data on tree level charged current transitions, in particular $u \rightarrow d$, $u \rightarrow s$, $b \rightarrow u$ and $b \rightarrow c$, allows us to set bounds on four elements of \tilde{V}_0 .

$$|\tilde{V}| \sim \begin{pmatrix} < 1.4 & < 1.4 & 1.0 \pm 0.4 \\ - & - & < 2.0 \\ - & - & - \end{pmatrix} \times \left(\frac{10^{-3}}{\epsilon_R} \right). \quad (2)$$

Note that elements of \tilde{V} and ϵ_R appear only in combination, where ϵ_R gives the size of the effective RH charged current coupling (normalized to the SM left-handed one). Unitarity of the first row puts a significant constraint on the value of ϵ_R

$$|\epsilon_R| = \left(|\epsilon_R \tilde{V}_{ud}|^2 + |\epsilon_R \tilde{V}_{us}|^2 + |\epsilon_R \tilde{V}_{ub}|^2 \right)^{1/2} = (1.0 \pm 0.5) \times 10^{-3}, \quad (3)$$

being in agreement with the result from naive estimates using coupling coefficients of $\mathcal{O}(1)$ and a scale of $\Lambda \approx 3$ TeV. From the unitarity of the third column one can deduce that the large $|\tilde{V}_{ub}|$ constrains the maximal value of $|\tilde{V}_{tb}|$. A large value of $|\tilde{V}_{tb}|$ is welcome since it minimizes the contribution to the elements $|\tilde{V}_{ts}|$ and $|\tilde{V}_{td}|$ contributing to FCNCs which are highly constrained. Also it could help to improve the agreement with $Z \rightarrow b\bar{b}$ in the RH sector with experiment. A global fit maximizing $|\tilde{V}_{tb}|$ is performed. From this fit we conclude that the RH mixing matrix is well described by the following ansatz

$$\tilde{V}_0^{(\text{II})} = \begin{pmatrix} \pm \tilde{c}_{12} \frac{\sqrt{2}}{2} & \pm \tilde{s}_{12} \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} \\ -\tilde{s}_{12} & \tilde{c}_{12} & 0 \\ \tilde{c}_{12} \frac{\sqrt{2}}{2} & \tilde{s}_{12} \frac{\sqrt{2}}{2} & \pm \frac{\sqrt{2}}{2} \end{pmatrix}, \quad (4)$$

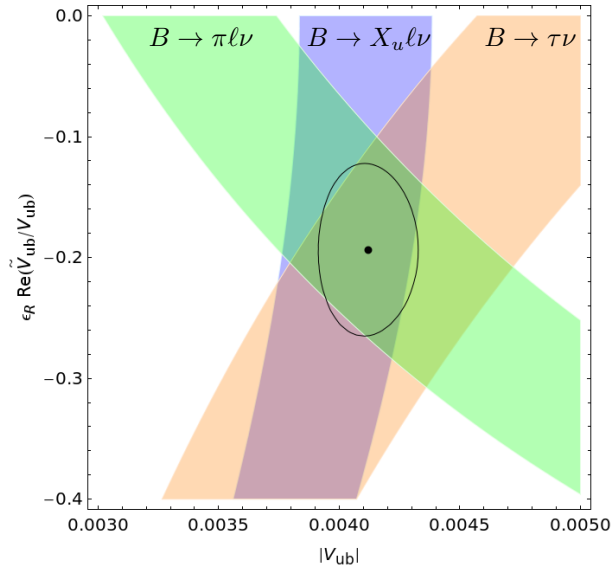


Figure 2: Constraints on $|V_{ub}|$ and $\epsilon_R \text{Re} \left(\frac{\tilde{V}_{ub}}{V_{ub}} \right)$ from $B \rightarrow \pi \ell \nu$ (green), $B \rightarrow X_u \ell \nu$ (blue), and $B \rightarrow \tau \nu$ (orange). The bands denote the $\pm 1\sigma$ intervals of the various experimental constraints. The ellipse denotes the 1σ region of our best-fit solution.

where we have only one free parameter.

Let us have a closer look at the \tilde{V}_{ub} element. In order to set a bound on $\epsilon_R \tilde{V}_{ub}$ we compare the effectively appearing CKM combinations to the values derived from the comparison of the SM with experiment. The structure of combinations of the CKM matrix and the new RH mixing matrix is easy to derive as the decay $B \rightarrow \pi \ell \nu$ is only sensitive to vector current, while $B \rightarrow \tau \nu$ is only sensitive to axial current. In the inclusive decay, a mixing between left and right components appears, which however turn out to be negligible. This allows us to set up three conditions. The global fit solution shown in figure 2, shows that in the presence of RH currents the discrepancy between inclusive and exclusive determinations is resolved. This is not the case in the SM case which corresponds to the top of the vertical axis, where the three determinations of $|V_{ub}|$ are clearly different. In presence of RH currents the true value of $|V_{ub}|$ turns out to be $(4.1 \pm 0.2) \times 10^{-3}$, selecting the inclusive determination as the true value.

3 $\Delta F = 2$ Processes

After having fixed the RH mixing matrix, we want to examine whether this new kind of mixing is consistent with low energy observables from particle anti-particle mixing and rare decays.

Let us first have a closer look at $\Delta F = 2$ processes. Within our framework new operators are generated, where we focus on contributions of the $\bar{Q}_R Y_u^\dagger Y_u \gamma^\mu Q_R$ bilinear, in particular

$$\begin{aligned}\mathcal{O}_{RR}^{(6)} &= [\bar{Q}_R^i (Y_u^\dagger Y_u)_{ij} \gamma_\mu Q_R^j]^2 \\ \mathcal{O}_{LR}^{(6)} &= [\bar{Q}_L^i (Y_u Y_u^\dagger)_{ij} \gamma^\mu Q_L^j] [\bar{Q}_R^i (Y_u^\dagger Y_u)_{ij} \gamma_\mu Q_R^j].\end{aligned}\quad (5)$$

This RR and especially the LR structure are known to be dangerous due to renormalization group effects (and in the case of ε_K also through chiral enhancement). The effective Hamiltonian reads

$$\mathcal{L}^{\Delta F=2} = \frac{c_{RR}}{\Lambda^2} \mathcal{O}_{RR}^{(6)} + \frac{c_{LR}}{\Lambda^2} \mathcal{O}_{LR}^{(6)}, \quad (6)$$

where c_{RR} and c_{LR} are flavour-blind dimension-less coefficients, whose size will be discussed later. Hence the RH mixing is only determined by the elements of the RH mixing matrix in particular by \tilde{c}_{12} , \tilde{s}_{12} and CP violating phases.

How does this RH mixing matrix now contribute to the different processes? The structure is summarized in table 1. The strong constraints of the K system mainly by

Mixing term	K -mixing $s \rightarrow d$	B_d -mixing $b \rightarrow d$	B_s -mixing $b \rightarrow s$
$\tilde{V}_{ti}^* \tilde{V}_{tj}$	$\frac{1}{2} \tilde{c}_{12} \tilde{s}_{12} e^{i(\phi_2^d - \phi_1^d)}$	$\pm \frac{1}{2} \tilde{c}_{12} e^{i(\phi_3^d - \phi_1^d)}$	$\pm \frac{1}{2} \tilde{s}_{12} e^{i(\phi_3^d - \phi_2^d)}$

Table 1

ε_K point towards either a small \tilde{c}_{12} or \tilde{s}_{12} unless c_{RR} and c_{LR} are very small. Due to the enhanced value of $S_{\psi\phi}$ from CDF [4] and D0 [5] collaborations, we assume large CP-violating effects in B_s -mixing. Hence we choose \tilde{s}_{12} to be large, which then in combination with ε_K implies automatically negligible effects in B_d mixing. Roughly the RH mixing matrix will appear with the following structure

$$|\tilde{V}_0| \sim \begin{pmatrix} 0 & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \\ 1 & 0 & 0 \\ 0 & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{pmatrix}, \quad (7)$$

where the zero entries shouldn't be understood as exact zeros. Note that there are additional phases from the diagonal matrices shown in equation (1).

For a more detailed analysis we can consider the constraints from ε_K and B_s mixing simultaneously. Imposing

$$\frac{(\Delta M_s)_{\text{exp}}}{(\Delta M_s)_{\text{SM}}} \approx 0.96 \pm 0.15 \quad \text{and} \quad S_{\psi\phi} \approx 0.6 \pm 0.3, \quad (8)$$

these two conditions for B_s mixing allow us to set up a system of two equations which can be solved. One obtains conditions for coupling coefficients and phases, which we will apply in the latter analysis of rare decays. For example assuming the RR operator in (6) to be dominant ($c_{RR} \gg c_{LR}$), the solutions are given by

$$\begin{aligned} c_{RR} &\approx \pm 7.3 \times 10^{-3} \quad \text{and} \quad \sin(2\phi_{32}^d) \approx \mp 0.30, \\ c_{RR} &\approx \pm 2.3 \times 10^{-3} \quad \text{and} \quad \sin(2\phi_{32}^d) \approx \mp 0.95. \end{aligned} \quad (9)$$

We obtain coupling coefficients of $\mathcal{O}(10^{-3})$ which are substantially lower than the

operator	size of coefficient	suppression
RH charged current	$\mathcal{O}(1)$	tree level
$\Delta F = 2$	$1/(16\pi^2) \approx 6 \times 10^{-3}$	loop

Table 2

$\mathcal{O}(1)$ Wilson coefficients determined from charged-currents. Naively the small value of c_{RR} doesn't seem natural, however this is perfectly fine when we understand $\Delta F = 2$ operators to be loop-suppressed with respect to charged current ones. This situation is summarized in table 2. The solutions for the parameters from B_s mixing also satisfy the kaon bounds.

4 Effects due to $\sin(2\beta)$ enhancement

Let us have a closer look at ε_K . As RH currents choose the inclusive determination giving the “true” $|V_{ub}|$, the value for $\sin(2\beta)_{\text{tree}}^{\text{RH}} = 0.77 \pm 0.05$ obtained from tree-level determinations is substantially higher than the corresponding result obtained in the SM, where the inclusive and exclusive determinations of $|V_{ub}|$ are averaged. It follows that the tension between the experimental value of ε_K and its prediction within the SM is automatically resolved within our framework. However as the NP contribution to B_d mixing is constrained to be negligible, we expect $S_{\psi K_S}^{\text{RH}}$ to be significantly larger than the experimental value $S_{\psi K_S}^{\text{exp}} = 0.672 \pm 0.023$ [6]. As a result the existing tension between these two values increases. Our result is about 2σ larger than the measured value. That means that $S_{\psi K_S}$ cannot be solved by RH currents alone in this framework. However a significant lower measured value of $S_{\psi\phi}$ might allow effects in B_d mixing, which could lead to a high enough new phase in B_d mixing and then ease the tension.

5 Analysis of rare decays and $Z \rightarrow b\bar{b}$

We now take a look at $Z \rightarrow b\bar{b}$ and rare decays. The main contribution is arising from a new effective coupling from the Z boson to RH down type quarks. We have applied

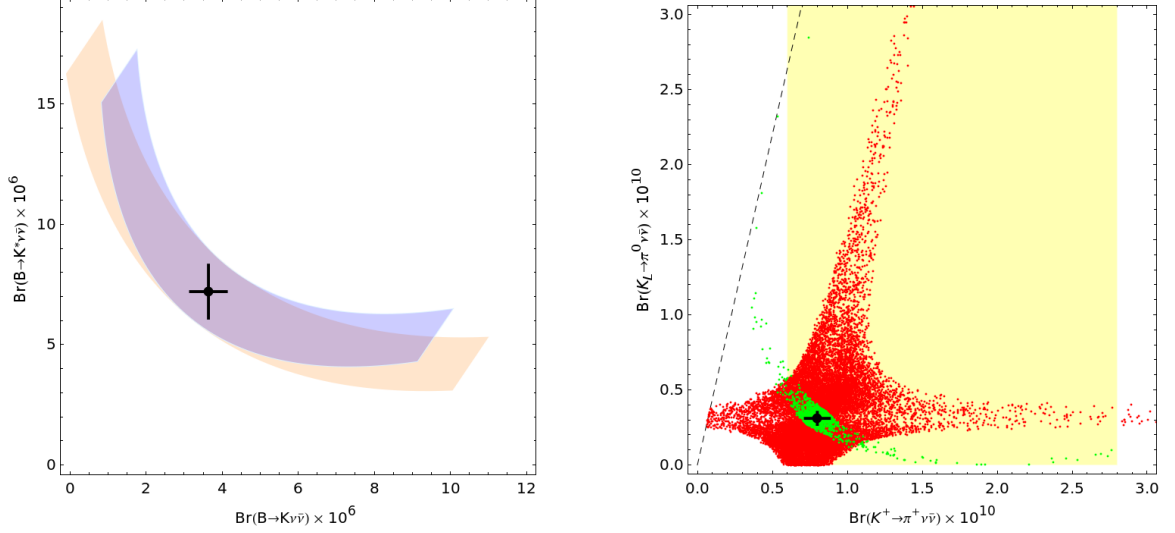


Figure 3: left: Correlation between $\mathcal{B}(B \rightarrow K\nu\bar{\nu})$ and $\mathcal{B}(B \rightarrow K^*\nu\bar{\nu})$, right: Correlations between $\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu})$ and $\mathcal{B}(K_L \rightarrow \pi^0\nu\bar{\nu})$

our analysis to a number of processes of which I will here only present a selection. First of all we find that the constraints from $B_{s,d} \rightarrow \ell^+\ell^-$ eliminate the possibility of removing the known anomaly $Z \rightarrow b\bar{b}$ in the RH sector. Furthermore the constraint from $B_s \rightarrow X_s \ell^+\ell^-$ precludes $B_s \rightarrow \mu^+\mu^-$ near present experimental bound. The deviations in $\mathcal{B}(B_s \rightarrow \mu^+\mu^-)$ can still be $\mathcal{O}(1)$, but push the effects in $\mathcal{B}(B_d \rightarrow \mu^+\mu^-)$ to be small or negligible when using the constraints from $S_{\psi\phi}$.

In addition interesting correlations can be found. Figure 3 shows the correlation between $\mathcal{B}(B \rightarrow K\nu\bar{\nu})$ and $\mathcal{B}(B \rightarrow K^*\nu\bar{\nu})$. We show two bands corresponding to the values of equation (9), a blue (dark gray) band for $|\sin(2\phi_{32}^d)| = 0.95$ and an orange (light gray) band for $|\sin(2\phi_{32}^d)| = 0.30$. We observe a clear anti-correlation. Both branching ratios can be enhanced by more than a factor of two over the SM value, which is shown as a black dot with the corresponding error bars.

Also a specific pattern is obtained for the correlations between $\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu})$ and $\mathcal{B}(K_L \rightarrow \pi^0\nu\bar{\nu})$ imposing the constraints from ε_K and $S_{\psi\phi}$. This correlation is shown in Figure 3. Depending on which operator dominates $S_{\psi\phi}$ we obtain a different correlation due to different conditions on the phases. Assuming c_{LR} to be dominant (shown in green/light points) the situation is more constrained. For dominant c_{RR} (shown in red/dark points) $\mathcal{O}(1)$ deviations from the SM are possible. With larger deviations we end up in a more fine-tuned scenario. The phase of ϕ_{12}^d has to be tuned in order to satisfy the ε_K constraint. As noted by [7], this structure is characteristic for all NP frameworks where the phase in $\Delta S = 2$ amplitudes is the square of the CP-violating phase in $\Delta S = 1$ FCNC amplitudes.

6 Conclusions

Summarizing in short the advantages and disadvantages of the RHMFV model. RH currents provide a solution to the V_{ub} problem. In addition the $S_{\psi\phi}$ and ε_K anomalies can be understood. However the $Zb\bar{b}$ problem cannot be resolved. The tension between $\sin 2\beta$ and $S_{\psi K_S}^{\text{exp}}$ becomes stronger due to the fact that we implemented a large $S_{\psi\phi}$. Furthermore, when taking $S_{\psi\phi}$ large, the effects in both B_d mixing and rare B_d decays turn out to be negligible. A well-defined pattern of correlations were obtained in various decays.

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